Renewable and Sustainable Energy Reviews 18 (2013) 478–485

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Forest-based bioenergy in China: Status, opportunities, and challenges

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ARTICLE INFO

Article history:
Received 1 August 2012
Received in revised form
22 October 2012
Accepted 27 October 2012
Available online 23 November 2012

Keywords:
Renewable energy
Biodiesel
Ethanol
Woody biomass
Policy
Plan

ABSTRACT

Forest-based bioenergy is gaining global popularity due to its multiple benefits and increased global energy needs. In this study, the current status of forest-based bioenergy in China was reviewed and the opportunities and challenges were analyzed. The latest national development plan for forest-based bioenergy was also discussed. It can be concluded from the study that forest-based bioenergy is still in the beginning stage in China but will grow rapidly in the next decade due to abundant resources and strong government support. However, there are major constraints that need to be addressed including unstable feedstock supply, low market interest and investments, inadequate R&D, and competition from other forest products. The national development plan sets up a mid-term goal for developing forest-based bioenergy but more supporting policies are required to guarantee its successful implementation.

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1. Introduction

The world is facing the dilemma of decreasing the use of fossil fuel in order to lower greenhouse gas emissions, while, at the same time, providing adequate energy for maintaining growth and development. This is not an easy to solve problem. Greenhouse gas emissions from the combustion of fossil fuel increased by 29% from 2000 to 2008[1]. On the other hand, rapid industrialization in emerging countries such as China and Brazil has driven the global demand for energy up at a rate of 3% per year [2]. Governments across the globe are turning to

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1364-0321/$ - see front matter
http://dx.doi.org/10.1016/j.rser.2012.10.044

low-emission renewable energy for answers. Among them, bioenergy is considered the preferred solution because of its multiple benefits.

Bioenergy currently provides about 10% of the primary global energy supply [3]. It is estimated that bioenergy has the potential of providing anywhere from under 10% to more than 60% of the world's primary energy supply [4]. Biomass, as an alternative to fossil fuels, can significantly reduce CO_2 emissions. Estimates put the range of greenhouse warming potential (GWP) offset measured as CO_2 equivalent to be 100–2070 Mt y^{-1} from producing 2–22 EJ y^{-1} bioenergy by 2020 [2]. Replacing fossil fuels with bioenergy has additional benefits. For example, it will increase energy security in regions without abundant fossil fuel reserves [5]. Low-Input-High-Diversity biomass can provide many ecosystem services including renewal of soil fertility, cleaner ground and surface water, and maintenance of wildlife habitats [6].

However there have been questions regarding the sustainability of crop-based bioenergy production. People are concerned about the competition for use of arable lands for energy production and other uses such as food supply, animal feed, and ecosystem services [7]. It was found that biodiversity has been reduced by about 60% in corn and soybean fields in the United States and by 85% in Southeast Asian oil palm plantations compared to unconverted habitats [8]. Also the expected CO_2 offset from using bioenergy may not be realized. One study shows that conversion of rainforests, savannahs or grasslands to produce crop-based biofuel in Brazil, Southeast Asia, and the United States could lead to more emissions. The magnitude of emitted CO_2 can be 17 to 420 times more than the annual greenhouse gas reductions that can be achieved by replacing fossil fuels with biofuel [9]. Increased crop-based bioenergy production bears other environmental problems such as monoculture and water pollution [4]. Even if 100% of the global yield of corn, sugarcane, soybean, and palm oil were converted into biofuel it would equal only 3% of the global primary energy use from fossil fuel combustion. The net energy supply after accounting for energy consumed in the conversion process is merely 1.2% [5].

Still competitive bioenergy can be generated when utilizing feedstock produced with lower greenhouse emissions than fossil fuels and with little or no competition with food production. For example, wood and forest residues harvested in a sustainable way are considered feedstock [10]. Woody biomass crops also have the potential to complement intensive agriculture and ameliorate its environmental impact [11]. Another desirable benefit is that bioenergy plantations have higher economic efficiency than long-rotation forests for the purpose of carbon sequestration [12]. Even without adding new bioenergy plantations, the existing forest resources hold great potential for producing forest-based bioenergy. Energy contained in the annual biomass harvested from forests in the Northern Hemisphere is about 107% of that generated from liquid fuels in the United States [7]. Production of bioenergy from forest biomass will not compete with the traditional use of wood. It was projected that by 2050, the global bioenergy potential from logging and processing residues and wastes alone would be equivalent to 2.4 Gm^3 y^{-1} wood under a scenario of medium demand for industrial round woods and firewood [13].

Bioenergy has special meaning to China. China is already the largest importer of oil and the second largest consumer of energy in the world. It was projected that the annual energy demand would grow by 4–5% per year through 2015 [14]. An additional incentive comes from the fact that China surpassed the US as the biggest CO_2 emitter in 2008. International pressure on China to cut carbon emission is mounting [15]. China plans to increase the share of renewable energy in its total energy mix from 7.5% in 2005 to 15% by 2020. Bioenergy will constitute about 3% of that supply [16]. With governmental policies and financial incentives in place, China's crop-based bioenergy industry is growing quickly, although experiencing the same rise and fall in popularity as in the rest of the world. China is currently transitioning from crop-based bioenergy to non-crop based bioenergy. Although forest biomass is expected to play an important role in this process the status of forest-based bioenergy in China and the major influencing factors are still not very clear. There are many unanswered questions. Does China have the potential to develop forest-based bioenergy? What quantity of bioenergy products can be extracted from forests in China? Which type of bioenergy should be the main focus? What factors will restrict its development? A few studies attempted to address some of these questions but they are limited by the availability of data and input from policy-making agencies [17,18].

This study provides a review of the development of forest-based bioenergy in China and addresses the aforementioned questions. Major objectives of the review include: (1) to summarize the current status of forest-based bioenergy in China, (2) to identify opportunities for developing forest-based bioenergy and analyze the latest governmental development plan, and (3) to discuss challenges that will be faced by forest-based bioenergy in China.

2. Current status

2.1. Current status of crop-based bioenergy

Feedstock used for crop-based bioenergy production in China mainly includes crops, crop residues, and agricultural wastes. The most successful bioenergy program in China to date is biogas production in rural areas using agricultural wastes. By 2009, 30.5 million household biogas digesters were installed and 12.4 km^3 of biogas were produced in China. Currently biogas is primarily produced and consumed on-site by rural households. New initiatives are underway to generate electricity from medium and large-scale biogas plants using manure and sewage [19]. There is still a huge potential for the development of biogas as only 19% of the rural households in China have adopted the technology [20].

It is technically plausible to produce biodiesel from edible vegetable oils in China. However, China can only produce enough edible vegetable oil to meet 41% of its domestic consumption and must import the rest. There is a slight possibility that cotton seed oil can be used for producing biodiesel as its use as edible oil is declining [21]. Because the edible vegetation oil is sold at a much higher price than that of biodiesel, it is currently economically impractical to produce biodiesel from edible vegetable oils in China. More than 100 biodiesel enterprises are mainly dependent on reusing waste cooking oils and animal fats as feedstock.

Ethanol production in China started in 2000 with strong government support. By 2008, ethanol production based on corn and grains reached a peak of 1.94 Mt, third after the United States and Brazil. However, due to concerns about food security the central government halted the construction of any new crop-based ethanol projects after 2007. Non-food crops such as sweet sorghum, cassava, and sweet potato have the potential to provide feedstock for an estimated output of between 19 and 50 Mt of ethanol by 2020 but the prediction hinges on improved conversion technology and the availability of land [22]. Experimental production of ethanol from stalks of corn, sweet sorghum, and sugarcane has been tested in eight pilot and demonstration plants, with a total capacity of 280,500 t y^{-1} [23]. Nevertheless the industrial production of cellulosic ethanol remains a challenge due to technological difficulties and the high cost [24].

Crop residues, mainly corn stalks and rice and wheat straws, are used for direct burning, biomass power generation, and biomass briquettes. According to one estimate, China produces about 630 Mt of crop residue annually. About 37% of crop residues are used as fuel by rural households and 20.5% are discarded in

the field. The amount consumed by rural households is expected to decrease as they have more disposable income to buy other types of fuels. It would seem that a significant amount of crop residues can be used for biomass power generation [25]. Nevertheless this seemingly abundant resource is dispersed over a large area. The costs associated with collection, transportation, and storage make the raw material supply expensive and unstable. The installed capacity of biomass power generation reached 4 GW by the end of 2009 but most power plants operate only 30%–40% of the time due to the shortage of feedstock. Due to high operating costs and inadequate subsidies only 1/3 of the biomass power plants can make a profit [26]. Biomass briquettes made from crop residues are still produced on a small scale with an annual production of around 0.1 Mt, less than 20% of the annual output of the United States [27].

In summary, crop-based bioenergy will still play a significant role in China, mainly in the form of biogas and fuels. The potential of producing ethanol from non-food crops is huge but faces challenges in technology and availability of land.

2.2. Current status of forest-based bioenergy

Forest-based bioenergy is not very visible in China today except for the firewood traditionally used by rural households. The importance of firewood is declining; its contribution to the total energy consumption in rural areas dropped from the 29% in 1991 to 21.2% by 2008 [20]. One main use of woody biomass is direct burning in power plants for generating electricity. Most of the biomass power plants in China use woody biomass to supplement crop residues. As of today, there are only two power plants that use woody biomass as the primary feedstock. The one located in Inner Mongolia has been in operation since 2009. It uses biomass produced from coppice of desert shrubs as primary feedstock for two 15 MW generators. Another one has been approved by the central government but is not yet in operation. A pilot program located in Jilin Province is producing wood briquettes from forest residues and wastes. The factory can turn out 15,000 t of wood briquettes annually.

Biodiesel programs have been initiated by the State Forestry Administration of China (SFA) and the three largest state-owned oil companies, PetroChina Company Limited (PetroChina), China Petroleum & Chemical Corporation (SinoPec), and China National Offshore Oil Corporation (CCNOOC). A series of demonstration projects have been installed in southwest and southeast China to produce biodiesels from seeds harvested from Jatropha (*Jatropha curcas*) plantations since 2007. These programs will produce a total of 0.17 Mt of biodiesel if completed. Up until now around 0.13 million ha of Jatropha plantations have been established but production of biodiesel is still at the trial stage. It was reported that the current yield of biodiesel from crude Jatropha oil was less than 100 t [28]. Several other woody oil plants have been grown as potential feedstock for making biodiesel (Table 1). Those numbers represent the most up-to-date statistics of the planting areas of woody oil plants in China.

Table 1
Areas of tree plantations for biodiesel production in China. Data were extracted from reports submitted to the SFA by provincial forestry administrations in 2010.

Species	Provinces	Planted area (km^2)
Camellia oleifera Abel.	Guangxi	3,666.7
	Jiangxi	7,466.7
Jatropha curcas L.	Guangdong	19.8
	Guizhou	66.7
	Sichuan	673.3
	Yunnan	880.0
Pistacia chinensis Bunge	Anhui	53.3
	Henan	1,333.3
	Shanxi	10.0
Sapindus mukorossi Gaertn.	Fujian	140.0
Sapium sebiferum (Linn.)Roxb.	Guizhou	77.3
Swida wilsoniana (Wanger.) Soják	Hunan	150.0
	Jiangxi	400.0
Vernicia fordii (Hemsl.) Airy Shaw	Guangxi	1,333.3
	Guizhou	1,369.7
Xanthoceras sorbifolia Bunge	Inner Mongolia	1,333.3
	Shanxi	23.6

Large scale production of forest-based ethanol is still in the conceptual stage. Although there have been good results with generating ethanol from lignocellulosic biomass in research laboratories and ***small-scale testing factories, industrial production is not feasible at this time [29]. Efforts to produce gas and liquid fuel such as hydrogen and bio-oil through thermal-chemical conversion of lignocellulosic biomass are in a similar situation [30].

3. Opportunities and challenges

3.1. Opportunities

Clearly forest-based bioenergy in China is still in the infancy stage. However, fast growth can be expected due to a combination of abundant resources and supportive governmental policies.

One fundamental argument for developing forest-based bioenergy in China is that it will not compete with agricultural production for land. All new energy forests will be planted on land that is not suitable for crop production. Results from several studies show that there are around 54 million ha barren hills and wasteland suitable for afforestation [31,32]. Trees can also be planted on marginal land. It is estimated that China has anywhere from 43.75 million ha to 6% of the national territory of marginal land [32–34]. Initial results from a 2010 survey of 21 provinces conducted by the SFA indicated that 12 million ha of marginal land are suitable for planting energy forests.

The diversity of forest tree species in China provides a good basis for forest-based bioenergy. There are around 30 woody oil plant species with greater than 40% oil content in the fruit. Most of these woody oil plant species can adapt well to harsh environmental conditions and have a long harvest period [35]. Table 1 shows the eight species that have been widely planted as plantations. Additionally 3 million ha of woody oil plants are scattered in the wild [36]. Seeds of the *Quercus* family contain more than 50% starch. There are about 18 million ha of trees in the *Quercus* family growing in forests in China. The estimated annual production of seeds is around 10 Mt that can, theoretically, yield 2.5 Mt ethanol. Roots of many under-canopy species also contain high concentrations of starch. One species, *Radix pueraria*, with 30% starch content and an annual production of 1.5 Mt, is especially promising. If fully utilized, 0.5 Mt of ethanol can be produced from this species alone [27].

Forests in China can supply a significant amount of sustainable woody biomass. According to the Seventh National Forest Resource Inventory, the forest cover in China has reached 20.36% giving it a total biomass of around 18 billion tons. Based on the inventory, the amount of forest residues is estimated at around 197.2 Mt y^{-1} [18]. Combined with the production of firewood and residues from managing shrubs, the total quantity of woody biomass that can be utilized reaches over 300 Mt y^{-1} [37]. A large-scale forest management program that was started in 2011 will provide additional sources. This program hopes to improve the quality of existing forests with a special fund of $300 million USD allocated annually from the central government to manage at least 30 million ha of forests. The forest residues and

wastes produced from this large-scale forest management program will become another stable source of biomass. Unlike crop residues, woody biomass generated from forests is concentrated in several areas, mainly the Southeast, Southwest and Northeast regions, and the Xinjiang provinces [38]. This will help lower both the collection and transportation costs.

The development of forest-based bioenergy in China fits well with the national strategies for CO_2 emission reduction and rural development. In the Copenhagen meeting the Chinese government committed to adding 40 million ha of forest plantations by 2020 as an important measure to combat global warming. Almost all these forest plantations will be planted on barren hills, waste land, and marginal land. These sites are not suitable for commonly planted timber and fruit tree species but can be planted with tree or shrub species with good stress-tolerance. It is a good opportunity for energy forests as many species with high biomass or seeds with high oil content adapt well to poor site qualities. The carbon emission from using forest biomass produced on marginal lands is low or neutral if managed carefully [10]. Carbon credits can also be generated from afforestation and reforestation activities under the clean development mechanism (CDM). Along with the environmental benefits, the economic return from forest-based bioenergy will help to increase the income of the rural population. China is currently reforming the forest tenure system in collectively-owned forests. About 55.4 million rural households now own 78.7 million ha of collectively-owned forests in the format of the house responsibility system [39]. Production of feedstock for bioenergy industry would provide an alternative to timber production as a way of generating income.

The majority of Chinese experts in the field of bioenergy agree that the government plays a dominant role in the development process of forest bioenergy in China [40]. Governmental policies have a significant impact on the growth of the industry. Currently a series of policies have been announced that support the bioenergy industry (Table 2). These policies provide strong political and financial incentives for the development of forest-based bioenergy.

3.2. Challenges

Despite having abundant resources and strong government support, forest-based bioenergy in China faces considerable practical difficulties. Some of these difficulties are problems shared by bioenergy industries in general, such as unstable feedstock supply, the relatively low-energy density of biomass compared with fossil fuels, and difficulties in securing sufficient funding [2]. Other problems are unique to China: inadequate research and development in key science and technologies, and strong competition from the paper and wood panel industries. These major challenges are discussed in detail in the following paragraphs.

Unstable feedstock supply is considered a major obstacle to the development of forest-based biodiesel in China. Although over 1 million ha are already planted with the five woody oil plants selected by the SFA as feedstock for biodiesel production, *C. wilsoniana, J. curcus, P. chinensis, X. sorbifolia, S. mukorossi*, most of these plantations produce unstable feedstock supplies because they are still too young or the plants are of inferior quality. An excellent example of this problem can be found in Yunan province's largest biodiesel company. The company planted 20,000 ha of Jatropha plantations to provide feedstock for a refinery with a designed capacity of 60,000 t y^{-1} of biodiesel. However, four years after the original plan, the refinery was redesigned into a testing production facility with a capacity of 3000 t y^{-1} due to the lack of feedstock. Extreme weather events and poor cultivars contributed to the low yield of these Jatropha plantations. This case illustrates one issue, only a few woody oil plant cultivars have been well tested and planted on a large scale in China [35]. Another factor which contributes to the unstable feedstock supply is the biodiesel industry's financial agreements with the grower. Companies offered financial assistance and high purchasing prices to entice farmers to plant bioenergy plants when the international oil market reached its peak; they dropped these incentives when oil prices dropped. The insecurity of the market has forced farmers to choose low-risk-and-low-profit traditional crops over high-risk-and-unstable-profit bioenergy plantations. Therefore breeding and planting good cultivars, constructing a large-scale feedstock supply base, and building a sustainable feedstock supply system are important strategies for developing a biodiesel industry in China [31].

The relatively low-energy density of forest biomass leads to the high cost of final energy products. Woody biomass has an energy density of 8 GJ t^{-1} (wood, 50% moisture) while that of coal is 28 GJ t^{-1}. This means that the transportation and storage costs of woody biomass are significantly higher than those of coal [41]. Along with the transportation costs, the special requirements for processing and storing biomass makes the unit construction cost of a biomass power plant twice as much as that of a coal-fired power plant [42]. These high costs erode the profit of biomass power generation. One way to reduce the transportation and storage costs of woody biomass is to process the raw materials into wood chips or pellets before transportation as they have much lower bulk volume than loose materials [43]. For example, the

Table 2
Major national policies that affect forest-based bioenergy in China.

Name	Year	Relevant contents
Renewable Energy Law	2006	Sets up the principals for developing bioenergy
Trial measures on management of cost-sharing for renewable energy power generation prices & expenses	2006	Stipulates the subsidy policies for biomass power generation
Interim measures on special fund management for development of renewable energy	2006	Gives special funding support for biomass power generation
Middle- and Long-Term Development Plan for renewable energy	2007	Sets up the targets of biomass power generation for 2010 and 2020 and associated supporting policies
Interim measures on subsidies for bioenergy and biochemical raw material bases	2007	Gives one-time subsidy of $454.5 USD per hectare for lands used for forestry biomass production
The Law of the People's Republic of China on Enterprise Income Tax	2008	Grants biomass power plants a 10% tax break on generated income
Notice on Value-Added Tax Preferences Policies for products related with comprehensive utilization of resources	2008	Waves the value-added tax for revenues from selling biomass power generated using forest wastes and biodiesel made from vegetation oils
Notice on Improving Pricing Policy for Agricultural Biomass and Forestry Biomass Power Generation	2010	Increases the price of electricity generated from biomass power plants to $110 USD MWh^{-1}
Notice on the Management of Biomass Power Generation Project Construction	2010	Regulates biomass power projects, including the project size, geographic concentration, and planning process
Standard for Biodiesel-Blended Fuel (B5)	2010	Sets up the standard for blending 2%–5% of biodiesel into diesels sell on the market

only power plant in China that relies primarily on woody biomass has successfully reduced feedstock costs by 1/3 by transporting chopped wood chips instead of pruned shrub branches.

Current investments in the forest-based bioenergy industry in China are very limited. The small scale of the industry, high costs, low profit margins, and insecurity of the market are major deterrents to market interest and financial investments. Few of China's forest-based bioenergy projects are supported by foreign loans or private companies; most are entirely or partially supported by governments or large state-owned companies [44]. Lack of funding is common in all stages of forest-based bioenergy production, including breeding cultivars, cultivating resources, converting and extracting, and scientific research.

R&D in China is far from adequate when compared to countries which lead in the development of forest-based bioenergy. In 2011 a survey was conducted by the National Energy R&D Centre for Non-Food Biomass (NECB) among 41 public and private research institutions in the forest-bioenergy field. The result showed that these institutions have made some progresses in the silviculture of Jatropha plantations, power generation using woody biomass, biomass gasification and briquetting techniques [45]. However, there are significant gaps between China and the leading countries in bioenergy production. China lags behind in the technology needed for industrial production of lignocellulosic ethanol, biodiesel, and hydrogen. Some advances have been reported in fast pyrolysis liquefaction and direct burning techniques but no major breakthroughs have been achieved. Except for a few tree species like *J. curcus, P. chinensis,* and *X. sorbifolia,* high-yield production techniques for feedstock are still not available. A sizable increase in public and private investments in R&D is required to address these limitations.

The forest-based bioenergy industry in China faces competition from the paper and panel industry. China is the largest wood-based panel production country in the world with a yield of 944.5 million m^3 in 2009. In the same period, the production of paper and paperboard reached 901.5 Mt [46]. Although China imports a large quantity of timber and pulp from abroad, the contribution from locally produced raw materials is significant. The situation may be explained using the example of the only power plant based on woody biomass. In that same region there are 10 factories that use desert shrubs as raw materials for making panels [47]. Competition drives up the price of raw materials. The transportation costs also rise as the power plant expands the area of feedstock collection. Although it is predicted that the competition may decrease slightly due to increased use of electronic media and paper recycling [7], a more immediate solution is to require forest-based energy enterprises to be constructed on a large-scale feedstock supply base.

4. The national development plan

4.1. Main contents of the plan

In order to advance forest-based bioenergy in China, the SFA released the National Development Plan of Forest-based Bioenergy (2011–2020) at the end of 2011[27]. The overall goal is that forest-based bioenergy will account for 3% of the renewable energy (i.e., 0.45% of total primary energy) supply by 2020. Woody biomass will constitute 70% of that amount and biodiesel and ethanol will constitute 25% and 5%, respectively. If the goal is reached by 2020, it will account for the fossil fuel equivalent of 20.25 Mt of standard coal.

To reach that goal, China plans to increase the total area of energy forests up to 18.99 million ha in order to produce enough feedstock (Table 3).

The recommended tree species are those that have already been planted widely. Processing techniques are already available for species used for producing biodiesel. Among them, *J. curcas* will account for 22.4% of total planted area. *X. sorbifolia* will accounts for 15.3%. *P. chinensis* will account for 13.6%. *S. mukorossi* and *S. wilsoiana* account for 3.9% and 4.5%, respectively. The remaining 40.3% will consist of other woody oil plant species, including *C. oleifera*, *V. fordii*, and other more localized species.

The target will be met by planting new plantations and improving existing low-quality energy forests. New plantations will be concentrated in regions with proven track records in cultivating the selected species and good access to processing facilities and markets (Fig. 1).

It is expected that the development of forest-based bioenergy will generate considerable ecological, economic, and environmental benefits. By 2020, the production of biodiesel from forest feedstock will reach 1.45 Mt y^{-1}.An additional 0.35 Mt y^{-1} of ethanol and 105 Mt y^{-1} of woody biomass can be produced. Based on the current market price, the revenue from producing feedstock alone can reach $7.39 billion dollars annually. This revenue will be a strong boost to the rural population's income. The 11.78 million ha of new forest plantations will generate significant ecosystem services such as reducing soil and water erosion and sequestrating CO_2.

The development plan also includes supporting measures to facilitate its implementation. These measures include the establishment of a coordinated production structure, financial stimulant policies such as tax reductions and subsidies, special development funds from governments, investments in R&D, and support from other forestry sectors.

4.2. Analysis of the plan

The main goal of the national plan, to increase the area of energy forests to 18.89 million ha, helps address the issue of unstable feedstock supply. The 11.78 million ha of new energy forests are designed to be part of the 40 million ha of forests that the Chinese government has already committed to plant. New energy forests are actually preferred because profits generated from selling feedstock can encourage farmers to maintain plantations, thereby alleviating the management burden of the government. The remaining 7.21 million ha of energy forest will come from existing low-yield forests that will be improved and managed by the ongoing large-scale forest management program. It is

Table 3
Planting areas and estimated yield of different types of forest-based feedstock specified in the national development plan.

Type	Total by 2015		Total by 2020	
	Planting area of feedstock (million ha)	Estimated yield (Mt y^{-1})	Planting Area of feedstock (million ha)	Estimated yield (Mt y^{-1})
Biodiesel	3.36 (2.90)[a]	0.50	6.43 (5.74)	1.45
Ethanol	1.03 (0.26)	0.10	3.13 (1.45)	0.35
Woody biomass	5.24 (2.43)	24.0	9.43 (4.59)	45.0
Forest residues	–	30.0	–	60.0

[a] The number inside the parentheses indicates new planting areas. The remainder will be existing low-yield forests that have been improved.

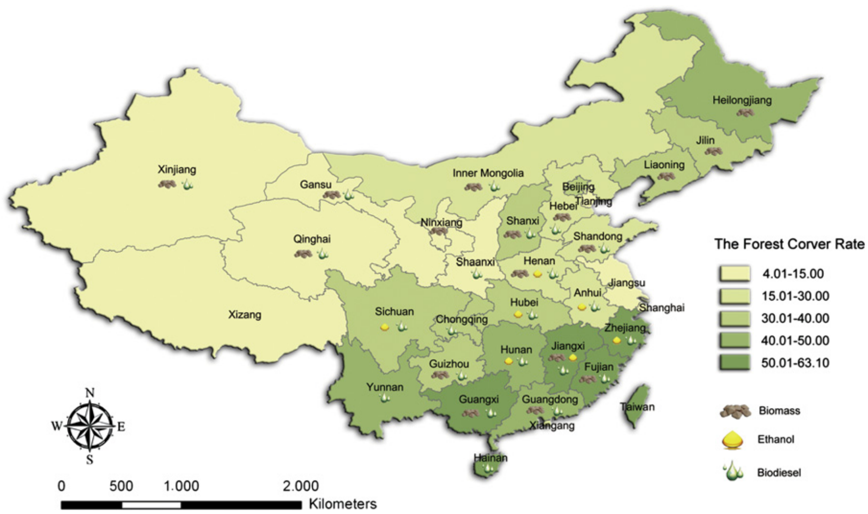

Fig. 1. The distribution of planned major feedstock supply bases in China. The current forest cover rate of each province is also shown for reference.

clear that the 2020 goal can be fulfilled by integrating the new program with existing forest programs with only a few modifications. This low-cost-high-return approach makes the plan both likely to succeed and turn a profit.

The plan addresses the high transportation cost of bioenergy by requiring forest-based bioenergy enterprises to obtain 50% of feedstock from their own feedstock supply bases. The plan also recommends that power plants are located close to the feedstock bases and energy markets to lower the logistic cost. An additional way of increasing the profit margin of bioenergy products is to produce multi-products by extracting high value products first and using the residue for lower value energy production [2]. An integrated production chain based on comprehensive utilization of feedstock and by-products should be the preferred format of forest-based bioenergy enterprises.

The national development plan mentions a series of economic policies to encourage investments from the private sector and cultivate the market. This could be the most uncertain part of the plan. The SFA needs to work with other government agencies to come up with favorable economic policies including subsidies, tax reduction, and loans for planting energy forests and producing bioenergy. Other agencies might have different priorities and, therefore, not be very responsive. Along with economic stimuli, negotiations with large oil companies are necessary to open up their distribution channels for biodiesel and ethanol produced from forest products. More actions should be taken by SFA and forest-based bioenergy enterprises to raise the general public's awareness about the benefits of forest-based bioenergy and to cultivate end-user markets.

Inadequate R&D has been addressed in the plan by calling for increased government spending to support research on selecting and cultivating high-yield tree/shrub species, harvesting and transporting feedstock, extracting and converting bioenergy products, and utilizing by-products. However, it should be noted in the plan that international collaboration is necessary to avoid duplication of efforts [48]. Technology transfer and direct investments from countries with advanced bioenergy industries should be encouraged and assisted by the government. North America and European countries can play important roles in that regard.

Finally, the need to balance bioenergy production and environmental protection was mentioned in the plan but not adequately emphasized. Based on lessons learned from past crop-based bioenergy production and large-scale afforestation projects, two principals should be strictly followed to reduce the environmental impact of forest-based bioenergy. First, the sustainability of resources should be given high priority. The development of forest-based bioenergy should not cause damage to forest resources and environments. Second, carbon emission from production of forest-based bioenergy should be managed to maximize carbon benefits.

In summary, the national development plan lays out the basic structure of forest-based bioenergy in China. It does a good job of tackling the issue of unstable feedstock supply but could use more work on addressing the economic and environmental aspects of forest-based bioenergy.

4.3. *Expected impacts of the plan*

As discussed in Section 3.1, the development of forest-based energy in China is mainly driven by governmental support. The passage and implementation of the plan will likely have a significant impact on the feedstock supply, extraction and conversion technologies, the bioenergy industry, and the market for bioenergy products.

Supply of woody biomass is expected to increase quickly. Fast-growing shrub species are used in new plantations. Using short-rotation coppice techniques, these new plantations can be harvested in 3–4 years. A consistent supply of woody mass can be achieved by carefully setting up a rotation system. At the same time, the large-scale forest management program conducted by the SFA will also generate significant amount of forest residues. Supply of feedstock for producing biodiesel and ethanol will increase slowly. Most woody oil plant species need eight years or longer to reach their productive age. Trials should be conducted to determine the time required for growth and the suitability of a species or cultivar before it is grown on a large scale. Time needed for a rigorous trial is normally long for woody species. The same issues apply to the production of starch-rich seeds from trees belonging to *Quercus sp.* Establishment of large-scale plantations will need considerable time.

Given the prospects of feedstock supply, the major format of bioenergy production in the next decade will probably be biomass power generation, including direct combustion, gasification power generation, biomass-coal co-firing power generation, and biogas power generation [49]. Even though direct combustion and biomass-coal co-firing power generation have been widely adopted by most biomass power plants in China, gasification power generation is considered the most promising technology for woody biomass because multiple products can be generated from the gasification process [50]. Besides heat and electricity,

chemical products like hydrogen, diesel, methane, and methanol can help to generate extra income, which will partially offset the high cost of biomass power generation. For these reasons, the development plan listed gasification power generation as the preferred technique. Enzymatic hydrolysis is listed as the preferred method for production of ethanol because it is more environmentally friendly than acid hydrolysis. So far, lignocellulosic ethanol production from woody biomass is restricted by difficulties such as lack of feasible pretreatment methods, low yield of enzymatic hydrolysis, and the ineffective conversion of xylose and arabinose [29]. Therefore, forest-based ethanol production will focus mainly on converting starch-rich seeds and roots. In the production of biodiesel, new processing techniques and catalysts such as the two-step process and solid base nanocatalyst need to be developed to replace the conventional, direct transesterification method [28].

The forest-based bioenergy industry will become more centralized. Small-scale bioenergy entities in rural China failed largely due to lack of technology, limited financial resources, reduced profitability and inconsistent government supports [51]. These lessons have been well noted. In the forest-based bioenergy development plan, the primary focus is on forming medium- to large-size plantation and production corporations. For example, six biodiesel production bases, each with an installed capacity of over 500,000 t y^{-1} biodiesel will be built. Every base will have its own plantations, harvesting and processing facilities, and marketing channels [27]. Because of the low-profits, high requirements for technology, and restricted market access faced by the bioenergy industry in China [52], decentralization is not a viable option for China's forest-based bioenergy corporations. One exception is the production of biomass briquettes. Small-scale factories targeting local markets are suitable for forested areas in China because only inexpensive and low-tech equipment is needed. This practice can cut down the transportation cost of forest biomass and increase its energy density.

The impact of the forest-based bioenergy industry on China's energy market is mostly localized. Forest-based bioenergy will only account for 0.45% of the total primary energy supply in China by 2020. High production costs make it hard for forest-based biofuel to compete with conventional fuels such as fossil fuels in the national market. The development plan also intentionally encourages the development of forest-based bioenergy in regions where abundant forest resources can be utilized to meet the energy needs at local and regional scales [27]. Internationally, China will continue to be a net importer of forest-based biomass. Importation of wood chips, charcoals, wood pellets, and forest residues by China is currently much higher than exportation [53]. China is also a net importer of liquid biofuel in the international market [54]. In the future, it can be expected that energy produced by increased production of forest-based biomass will be mainly consumed domestically due to increasing energy needs.

5. Conclusions

Bioenergy in China is in transition from crop-based to non-crop based. Forest-based bioenergy is an important part of this transition. The analysis of the current status of forest-bioenergy in China and the factors that affect it indicate that developing forest-based bioenergy almost from scratch will be a challenging task. Implementation of a well-considered national development plan feedstock supply will remove one obstacle to forest-based bioenergy. Processing and marketing are, however, two important factors that present uncertainties. Although some aspects of these two factors have been addressed in this review, more in depth studies are needed to examine how various combinations of technological advancements and economic situations can impact the long-term growth of forest-based bioenergy in China.

Acknowledgement

This study was supported and funded by State Forestry Administration of China (Grant no. 2011473 and 201204510). The authors would like to thank the Maowusu Biomass Power Plant for providing access and logistic support in the survey.

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